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Unification of contemporary negative bias temperature instability models for p-MOSFET energy degradation

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ABSTRACT

In this article, we present contemporary research advancements on negative bias temperature instability (NBTI) degradation models which are responsible for p-MOSFET energy degradation. Hence, we propose a unified theory on the recent models in order to predict the transistor aging by considering the energy effect. Development of the newly modified model in this article is followed by a reassesment on NBTI models considering energy degradation. Unlike many of the previous models, the proposed theory of NBTI degradation projects the reliability in both stress and recovery phase; which follows power law.

Contents

1. Introduction

In the field of engineering, reliability has always been an issue to affect system performance and energy consumption. In this regard, previously there has been works on mini and mega power systems [1,2]. Many of these works focused on reliability based modeling for improvising energy efficiency [3–5]. On the other hand, most of the power electronic devices we have around are mainly composed of integrated circuits (IC). And, CMOS is widely used in the IC implementation technology. We found that there are still scopes to work on the reliability aspect of energy efficiency of sub-nanometer CMOS structures. Energy shift of any CMOS system can be affected due to various reasons like hot carrier injection [HCI], time dependent dielectric breakdown [TDDB] and negative bias temperature instability [NBTI]. But among these, at high temperature and at nanoscale technology NBTI is the most dominant type of defect affecting reliability as per Mishra et al. [6]. In comparison with HCI and TDDB, for lower technology nodes, NBTI is the most catastrophic reliability issue to cause shift in threshold voltage, drain current, linear drain current, saturation current, channel mobility, subthreshold slope, off current and transconductance [7,8]. The degradation of threshold voltage and drain current cause energy degradation. Therefore taking [7,8] into account, energy degradation will be more due NBTI. Moreover, as geometric and process advancement continues further, NBTI becomes more catastrophic at a high temperature [9].

NBTI degrades transistor performance which mainly include threshold voltage, linear drain current, saturation current, transconductance, channel mobility, sub threshold slope and off current. The degradation of any of these parameters can result in

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semiconductor device failure [10]. And the dysfunction of semiconductor device can take place in IC technology, photovoltaic technology [11] and power electronics. As per Chakraborti et al., in recent years power electronics deal with high power. Reliability is one of the factors to affect the device selection criteria [12]. NBTI is a dominant form of reliability issue and it mainly occurs due to channel-length, oxide-thickness scaling and high temperature which is due to high power consumption at times. It occurs when a p-MOSFET is stressed with constant gate voltage at an elevated temperature in inversion mode. A lot of research works on the prediction of NBTI degradation have been performed in circuit level and in device level. Many models have been proposed to predict the lifetime of transistors. Conventional NBTI models are designed by considering the structure of broken or dangled Si–H bonds. Incorporation of nitrogen weakens the bond energy and as a result hydrogen is released. This creates traps which degrade circuit parameters and raises significant concerns to the formation of new NBTI models. This problem needs to be reanalyzed over the existing models.

One of the widely used models of NBTI is reaction diffusion (RD) model [13] which can be interpreted with energy by employing power- law dependence [14–16]. But, many other models do not follow the power law. Hence, still there are scopes to improvise these models by unifying the contemporary degradation models. This paper illustrates a review on the recently developed NBTI degradation models in device level and proposes unification techniques among different degradation models to recover the inadequacies of the previous models and to gain compatibility with power law. As, the proposed theory unifies the precise portions of two different models, it contributes to estimate NBTI degradation with higher accuracy over the previous works.

2. Reassessment of NBTI models

This section describes the prior and recent degradation models; which were analyzed in terms of energy degradation. Before moving further, it is important to state that transistor degradation can be divided into two parts; namely energy degradation due to stress phase and energy degradation in relaxation phase. When a voltage is applied on the gate of the transistor, we refer it as the stress phase. When there is no biasing, we refer it as relaxation phase. In relaxation phase partial energy recovery takes place. Therefore, in the case of NBTI, degradation is present in both phases [17]. In predicting degradation, both of these phases are taken into account. Having predicted the degradation in both phases suitable guardband can be put in the transistor for better reliability and sustainability. Hence, forming an accurate prediction model is very important.

This section is mainly divided into three subsections, where RD model and the model of Maricau and Gielen are discussed in the first two sections. The third subsection describes the most contemporary degradation models.

2.1. Reaction–diffusion (RD) model

One of the prior models to define NBTI was developed by Jeppson and Svensson [13], which is known as reaction–diffusion (RD) model. The model explains a field driven reaction in SiO_2 interface. This reaction impacts the Si–H bond and due to elevated temperature and negative stress, bond energy gets weaken. This either creates a dangling bond or breaks the bond by releasing hydrogen. Having explained the physics of dangled and broken Si–H bond, this model also describes the movement of hydrogen from SiO_2 interface to dielectric. Interface trap generated due to elevated temperature and negative stress in the gate of p-MOSFET engenders interface traps which follow power- law dependence, where the time exponent ranges from 0.16 to 0.25. Generated NBTI due to hole-produces interface trap has been explicated by RD model. RD model explains the following equations for NBTI [13].

$$\frac{dN_{IT}(t)}{dt} = k_f(N_0 - N_{IT}(t)) - k_r N_{IT}(t)) - k_r N_{IT}(t) N_H^0(t) \tag{1}$$

$$\frac{dN_H}{dt} = D_H \frac{d^2 N_H}{dx^2} \tag{2}$$

$$\frac{dN_{IT}}{dt} = D_H \frac{dN_H(x,t)}{dx}\Big|_{x=0} \tag{3}$$

Eq. (1) describes reaction whereas Eq. (2) defines diffusion during the operation of NBTI. Flux condition is described by the third equation, when interface trap starts generate. All these three equations are energy dependent and subject to initial number of Si–H bond before stress is applied and the number of hydrogen after stress is applied. N_0 denotes the initial number of Si–H bonds before applying the stress in the gate. Acceleration of the reaction from forward and reverse sides are, respectively, denoted by k_f and k_r. After the stress is applied and removed, a certain amount of hydrogen is formed at SiO_2 interface. Concentration and diffusion coefficient of hydrogen is defined by N_H and $D_{H,}$ respectively. As NBTI can be divided into two phases, namely stress phase and recovery phase. Though, the recovery phase is unable to explain the power law and stress phase follows it as per Alam et al. [14]. On the other hand as per Islam et al. [17], unlike stress mode, the power law cannot be explained by R–D model in recovery stage. But in stress phase the change of threshold voltage with respect to time remains linear for different stress voltage. As a result the power dissipation also remains linear. The model mainly deals with the association and disassociation of hydrogen which refers hydrogen as a carrier. One of the advantages is, hydrogen can play a stable and important role as a carrier [18].

RD model has been projected in Fig. 1. From the threshold voltage extracted from RD model simulation, we plotted threshold voltage change, dV_t with respect to measurement time. Fig. 1 shows the change of threshold voltage with respect to time. Like [14], Fig.1 shows power law dependence.

2.2. Maricau and Gielen

A comprehensive NBTI degradation model was presented by Maricau and Gielen [19]. Unlike R–D model, this model delineates the relaxation energy of NBTI along with the permanent trap. Due to high temperature, NBTI occurs and after the withdrawal of the stress voltage, recovery component remains; which is discussed in

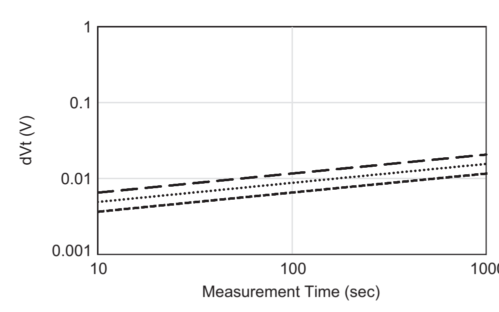

Fig. 1. Time evolution of NBTI V_T shift obtained from RD model for different stress bias.

this literature. This recovery component is related to hole trapping and de-trapping of pre-existing oxide traps. The permanent NBTI component is related to the formation of interface state. A model based on 1.4 EOT (Equivalent Oxide Thickness) CMOS processed with SiO_2 technology having width and length of 10 μm and 0.5 μm, respectively, is implemented here. The model shows a very good harmony with the measurement results on different p-MOSFETS at different time intervals. Over RD model, it shows better performance. On the other side, RD model fails to illustrate the recoverable part of NBTI. The interpretation of the model can be explicated from the summation of permanent degradation component P and recoverable component R, respectively, as per the Eqs. (4)–(6). The permanent degradation component is comprised of B_p, which is a foundry dependent parameter; V_{str} denotes stress voltage, p defining the rate of the slope created by the equation and n_{lim} is the limit of the slope which has a value of 0.16. On the other hand, the recoverable component R contains V_{ci} is the initial voltage of the capacitor, K is the constant and m is the number of RC (Resistor–Capacitor) element which is more than 25.

$$D = P(V_{str}, t_{str}) + R(V_{str}, t_{str}, t_{relax}) \tag{4}$$

$$\log(P) = \log(B_P V_{str}) + \int_0^t (t^{-p} + n_{\lim}) d\log(t) \tag{5}$$

$$R = \sum_{i=0}^{m-1} (V_{str} + (V_{Ci,0} - V_{str}) \exp(\frac{-t}{10^i C_0 K})) \tag{6}$$

2.3. Contemporary degradation models

Very few contemporary literatures have been found which only deals with device degradation models of NBTI. As per Alam et al. [14], NBTI is interface trap driven phenomena associated with broken Si–H bonds and it does not state the impact of recoverable portion after the impact of stress voltage. Though, Alam et al.[14] summarizes the pre-2003 literatures and reinterpreted RD model with 2003–2005 models [20–22]. From the pre-2005 literatures Alam et al. [14], finds seven key features of NBTI which are incompatible with the definition of the RD model. Hence, the reinterpretation of this model took place, which gives a solution for the contradictions of those seven key features. Though, the re-puzzled form of RD model explained stress time exponent, activation energy, field acceleration and frequency independence which are significant among the key features of NBTI.

Based on the impact of stress on NBTI Yang et al. [23], explained the dependence of NBTI degradation on stress temperature, stress voltage and channel length. Here, stress proximity technique (SPT) is used to examine the impact of stress on NBTI. SPT increases drive current of PMOSFETS by 19%. It reduces the threshold voltage degradation caused by NBTI, which also depends on stress time, stress temperature and stress voltage. SPT gives much lower NBTI induced threshold voltage degradation at a nominal operating voltage thus results in a much longer device lifetime. NBTI degradation is significant for shorter channel lengths and relative NBTI improvement by SPT is larger for shorter channel lengths.SPT enhances transfer of compressive strain into the channel and thus, it boosts the hole mobility which improves the device performance in terms of power consumption.

Here first principle calculation is carried out to check the effect of strain on NBTI. Change in bond angle is used as a parameter to simulate the strain into the calculation. Strain is favorable to Si–H dissociation; which is dependent on bonding energy of Si–H bond. Effect of strain on NBTI reaction is also studied by examining the influence of strain induced change in bond angle on reaction energy. Strain enhances the NBTI degradation in terms of reductions in both Si–H bonding energy and NBTI reaction energy.

He [24] represented a thorough tentative study of NBTI recovery under Variable Body Bias (VBB) conditions. Recovery dependence on VBB is studied on P+ polysilicon gate of p-MOSFETS with ultra thin oxynitride gate oxide having oxide thickness of 1.5 nm and nitrogen concentration of 1.5×10^{15} atoms/cm^2, which made by decoupled plasma nitridation. Periodic interruption during stress and recovery stage is examined to observe the device characteristics. The experimental results under Forward Body Bias (FBB) condition contradict traditional hydrogen related diffusion model. Both positive gate bias and FBB enhance the recovery. Forward VBB technique can improve the drive capability without degrading the NBTI lifetime. Enhancement of NBTI recovery by FBB gives longer lifetime compared to the typical AC stress.These results indicate that the Forward VBB technique improve the drive capability without affecting the NBTI reliability.

Deora et al. [25] used an ultrafast on-the-fly (UF-OTF) linear drain current technique to determine the short and longtime generation and recovery phase of NBTI. Plasma Nitrided Silicon oxynitride p-MOSFETS having different equivalent oxide thickness (EOT) and atomic density is used on a UF-OTF linear drain current setup. NBTI generation and recovery are strongly correlated. Though, trapped holes and generated interface trap which contributes to overall degradation aren't correlated. The measured power law time exponent during long time stress as a function of stress is shown here, which is obtained by the conventional measure-stress-measure (MSM) method at various delays as well as using OTF and UF-OTF methods.

Recovery during measurement delay causes an increase in power law time exponent. Longer time recovery shows strong temperature dependence due to the generated interface trap induced process. A bigger setback time in MSM outcomes in strong temperature dependence of power law time exponent. Decrease in postponement doesn't generate interface trap recovery and temperature independent recovery due to the trapped holes controlled method. So, power law time exponent remains free of stress when calculated using OTF or UF-OTF methods having minor setback time. Both initial stage of generation and recovery are dependent on weakly temperature dependent hole trapping and de-trapping method. Early recovery is biased by trapped holes de-trapping and the commencement of generated interface trap recovery is postponed. Longer time span is dominated by generation and passivation of interface traps strongly relative to temperature.

For the first time the effect of Grain Orientation (GO) on NBTI characteristics of metal gate devices is investigated and reported by Rasouli et al.,[26]. A metal gate material is used in p-MOSFET and GO induced work function variation (WFV) figured and demonstrated by conducting test.

Impact of oxide electric field on NBTI characteristics is examined using modified R–D model. Customization of R–D model represents the effect of gate oxide electric field on threshold voltage degradation which is underrated by 50% and GO effect is ignored.

A 3D simulator from SILVACO (ATLAS) was used to show the effect of GO on oxide electric field. Total gate region is classified into a number of sections. According to the standard size of the grains for a fixed type of gate material, each section's area is counted. Work Function of each section is determined according to the chances of the GO and corresponding Work Functions. It is seen that the effect of gate oxide electric field is miscalculated by 46% with respect to the condition where the impact of GO is included. Measured data in the report does not identify this fault since the wrongly estimated results are covered by fitting parameters like constant factor which don't have any physical approach.

Speed of recovery process is slow down due to impact of GO induced electric field after the gate-source bias is removed. Application of negative gate source bias makes higher hole concentration in FINFET device (active in inversion region) which causes degradation during the entire time. Variation in threshold voltage is increased highly due to grain orientation. Corresponding negative gate voltage matching with different WFV standard deviation in front gate and back gate of FINFET device during recovery process is shown.

In 2012, Gupta et al. reassessed NBTI considering four energy level in two different stages [28]. The prediction capability depends on the input parameters. Previously there was a common perception that 2-stage model is consistent with all features of NBTI degradation. But the reassessed research of Gupta et al. shows it is only consistent for short time DC stress. The authors conclude that this two stage energy model needs to be further modified in order to achieve consistency with experimental data.

One of the recent models related to NBTI and energy sustainability was shown by Karim et al. [29]. This model shows a statistical algorithm to predict energy dissipation due NBTI for circuit level only. In the same year, Hatta et al. worked on energy distribution probing techniques and its' behavior [9]. If core component or transistor degradation is to be analyzed, the technique of Karim et al. is not applicable [29]. On the other hand, Hatta et al. did not focus on energy sustainability prediction.

3. Discussion

In our previous section we reported a review on the degradation of NBTI and its impact on device level energy dissipation. From the review we found that it is not easy to come to an agreement on the physics of device level NBTI energy degradation model. Hence, from the analysis of the previous review works we will find the drawback of the models and hence, we will propose a new form of model for NBTI. This model is mainly comprised of two separate degradation models and has been described below.

From the pre-2005 research works, Alam et al. [14] depicted seven key features of NBTI which do not show a good agreement with RD model. Hence, the reformation of this model was done as a solution for the contradictions rose from those seven key features. Though, the reformation of RD model explained stress time exponent, activation energy, field acceleration and frequency independence which are significant among the key features of NBTI. Though, frequency independency is a matter of question when the frequency is higher (> 100 kHz). If frequency remains a doubtful parameter, definitely that will affect the energy level. On the other hand, the result found by Ielmeni et al. [27] shows NBTI degradation is dependent on frequency. As per Islam et al. [17], RD model failed in explaining NBTI recovery in relaxation stage due to the long term diffusion of H_2 in poly-Si. Maricau and Gielen [19] described NBTI degradation along with the recovery component where a better result was obtained in recovery stage over the results found by Alam et al. [14].

From the analysis of RD model it has been found that RD model has been critical in explaining NBTI energy degradation in relaxation stage. Though, Maricau and Gielen [19] focused on the relaxation component, but it does not explain the power law dependence, which is one of the key aspects of NBTI. The same statement can be made for the reports of He [24] and Deora et al. [25], as those do not show the impact of power law.

Rather than forecasting NBTI, Yang et al. [23] employs a technique to lower the instability by generating an extra amount of drain current. The report of Yang et al. [23] is a significant piece of work to deal with the instability. Though, Yang et al. [23], did not form any equation to predict NBTI. On the other side, the report of Deora et al. [25] focuses on the isolation of hole trapping and interface trapping to explain the energy recovery part of NBTI. Though, it does not state any equation for the recoverable part of NBTI.

From the above models, it is transparent that maintaining power law in stating an equation for NBTI is an issue which can be solved by the unification of prior degradation models. Summing up any other equation with R–D equation will also maintain the power law, as R–D model is one which follows the power law. On the other hand Maricau and Gielen [19], successfully describes the recoverable part which can be appended with the permanent part of R–D model. The unification shown in the proposed work can show a better result over RD model as it considers both stress phase and recovery phase by maintaining power law.

4. Conclusion

The review and the discussed proposal which are reported in this article shows a picture on different NBTI models considering the energy effect, re-modification of RD model by considering power law effect and by unifying the existing prior models, respectively. The proposed model follows the power law as the stress phase of RD model gives a good agreement with it. On the other hand, unlike the previous models, the summation of the stress phase with another model's recovery phase will give a clear picture on relaxation energy in terms of transistor reliability. Therefore, the prediction of NBTI degradation can be done accurately.

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